Cirrus, Contrails, and Radiative Forcing over the USA: Their Relationships to Air Traffic and Upper Tropospheric Conditions

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Abstract
Contrail coverage and optical properties over the USA are derived using AVHRR taken over the USA. Mean optical depth and particle effective diameter are 0.46 and 35 µm, respectively, for 55 contrails over different backgrounds. Mean coverage for the USA over 4 months is 1.8%. Although the detection algorithm overestimates the coverage, spreading is likely to produce even greater coverage.

Introduction

The areal coverage of cirrus clouds produced by persistent contrails is expected to increase as the global commercial fleet of aircraft grows. Current coverage by linear contrails that are detectable with meteorological satellites is estimated at 0.1% or 4.6 x 10^6 km^2 (Sausen et al. 1980). From models of projected air traffic, such contrails are expected to cover between 0.38 and 0.47% of the Earth's skies by 2050. Besides decreasing the amount of blue sky, contrails affect the radiation budget by trapping more longwave (LW) radiation than they reflect shortwave (SW) radiation. Using the assessments of linear contrail coverage and assuming a mean contrail optical depth τ = 0.3, Minnis et al. (1999) estimated that the current mean global contrail radiative forcing (CRF) is only 0.02 Wm^{-2}. This value is expected to rise to about 0.10 Wm^{-2} by 2050.

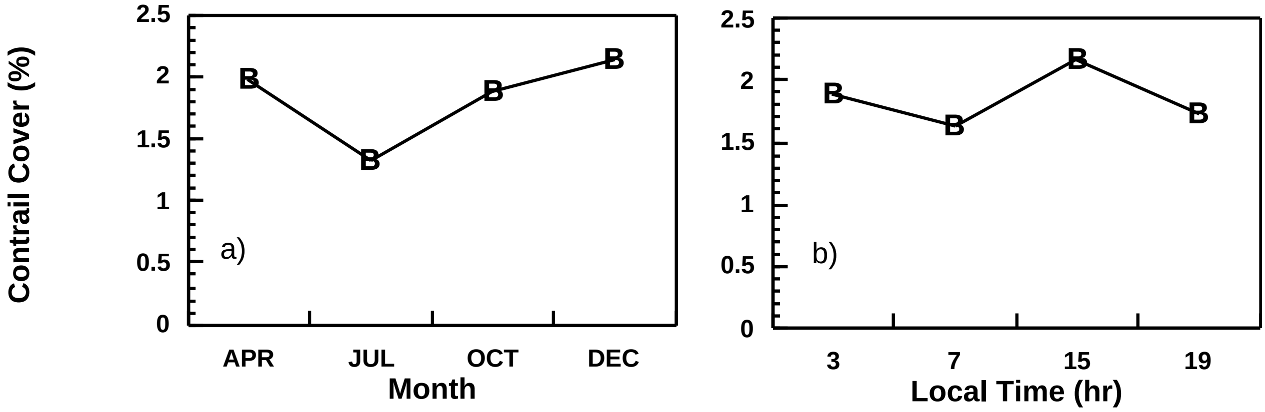
Many of the parameter values used to estimate both the contrail coverage and the radiative forcing are highly uncertain. Linear contrail coverage has not been measured directly over many parts of the globe, in particular, over the United States of America (USA) where air traffic is extremely heavy. Contrail optical depths have been measured remotely by some surface- and satellite-based instruments, but the statistics are neither complete nor robust. For example, Meyer et al. (personal communication, 2000) applied an infrared technique to Advanced Very High Resolution Radiometer (AVHRR) data and derived a mean τ of 0.11, which represents a 300% difference from the value currently used as the best estimate. Using multispectral visible and infrared techniques to track contrails with Geostationary Operational Environmental Satellite (GOES) data, Minnis et al. (1998) and Duda et al. (2000) found that contrails often grow into natural looking cirrus clouds with τ between 0.2 and 0.5. At their peak, the areal coverage of these contrails can be up to four times that of the linear contrails that would have been detected with the AVHRR data. Such studies are limited to a few cases, however, because of the difficulties inherent in tracking contrails in an environment that often contains natural clouds and newly forming contrails. To better determine and reduce the uncertainties in the current estimates of contrail coverage, particle size, optical depth, and radiative forcing, it is necessary to measure and estimate these quantities as accurately and comprehensively as possible. This paper describes the current results from an ongoing study of these contrail characteristics over the USA.

Linear Contrails

Contrail cover was derived from NOAA-11 (1430 equatorial crossing time EQT) and NOAA-12 (0730 EQT) 1-km AVHRR data using the linear contrail detection method of Mannstein et al. (2000). The data were received at Austin, Texas and nominally covered the entire contiguous USA, but were sampled less frequently over the coasts than over the interior because of less favorable lines of sight to the satellites off the coasts. Data from all of the available overpasses during April, July, October, and December 1993 were analyzed to provide contrail coverage and direct estimates of LW contrail radiative forcing. The latter is estimated by

$$CRF_{LW} = LW_{con} - LW_{bkgd},$$

where LW_{con} and LW_{bkgd} are the outgoing longwave radiative fluxes from the contrail pixels and the surrounding contrail-free pixels, respectively. The nearest three pixels on either side of the contrail are used to compute LW_{bkgd}. The longwave fluxes are derived from the infrared channel (11 µm, IR) brightness temperatures using the method of Minnis and Smith (1998).



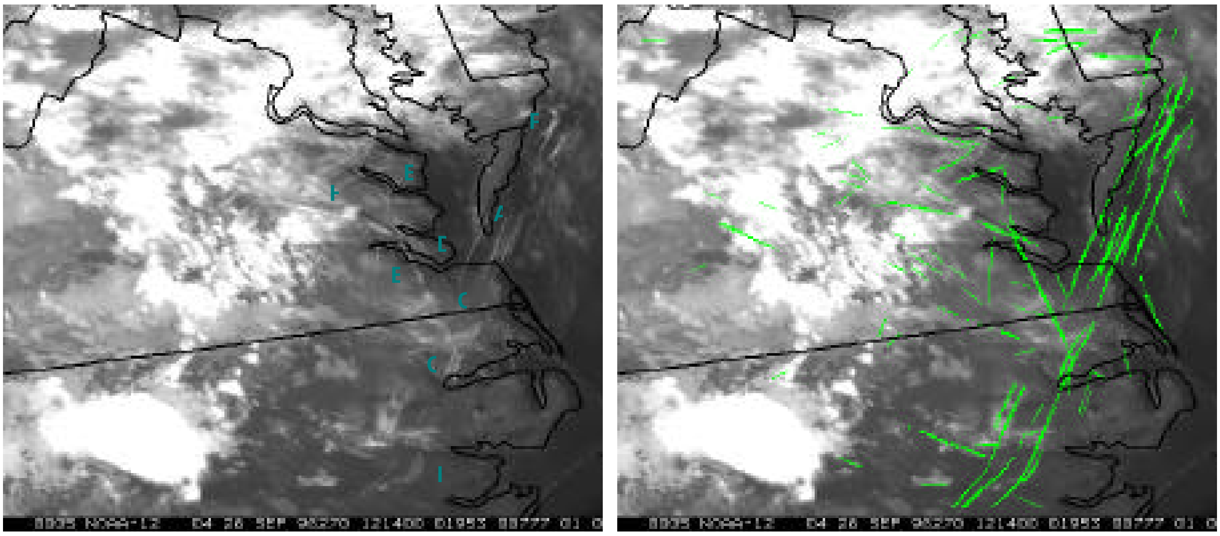
The monthly mean contrail coverage for the domain (25°N - 55°N; 65°W - 130°W) show in Fig. 1a follows a distinct seasonal cycle with a minimum during July and maximum during December. The mean diurnal variability plotted in Fig. 1b is less pronounced with a maximum of ~ 2.3% at 1500 LT.

Fig. 1. Monthly (a) and hourly (b) mean 1993 contrail coverage over the USA from AVHRR data.

Mean coverage for the 4 months is 1.8%. These results probably overestimate the true linear contrail coverage because the detection method sometimes classifies natural clouds as contrails. Using an interactive visual analysis, it was found that approximately 30% of the contrail coverage from NOAA-11 and 12 was due to false positive identification. Nevertheless, the means follow a seasonal cycle similar to that developed from theoretical calculations. Sausen et al. (1998) found a July minimum of 0.4% and an April maximum of 1.4% over the USA. Their mean is approximately 25% less than the observed value after it is corrected for the overestimate. The lack of a significant minimum at 0300 LT in Fig. 1b suggests that either the linear contrails are long-lived or that there are some additional detection problems at night when the surface is much colder than during the daytime. Air traffic is at a minimum at that time.

The mean contrail radiative forcing is determined by averaging the individual results by the contrail areal fraction. The mean LW forcing for the USA from the satellite data is 0.56 Wm^{-2} with negligible seasonal variations. The smaller contrail coverage during July is more effective in trapping radiation because the surface is warmest thereby maximizing the contrast between the contrail and surface temperatures. From the results of Minnis et al. (1998), it was found that CRF_{LW} over the USA averages 0.34 Wm^{-2} with a minimum of 0.24 Wm^{-2} during July. If the contrail cover overestimate is removed, then the AVHRR mean CRF_{LW} reduces to 0.39 Wm^{-2}, a value that differs by only 15% from the theoretical result. This comparison indicates that the linear contrail estimates are reasonable for current air traffic over the USA.

To determine the optical properties of the linear contrails, a sampling of various contrails observed in NOAA-12 AVHRR data were analyzed for τ, effective diameter D_e, and ice water path *IWP* using the visible IR solar-infrared split-window technique (VISST) used by Minnis et al. (1998). Figure 2 shows an example of contrails over eastern Virginia and North Carolina. On the left, the IR image shows several linear contrails identified by the adjacent letters. The image is repeated on the



	A	B	C	D	E	F	G	H	I
τ	0.37	0.25	0.42	0.28	0.22	0.49	0.14	0.21	0.20
D_e (μm)	18	19	25	14	30	21	45	30	21
LW_{CRF} (Wm^{-2})	24.2	13.0	21.7	7.0	5.2	16.8	6.7	6.9	4.7
SW_{CRF} (Wm^{-2})	-10.1	-2.6	-6.8	-2.2	-1.1	-7.1	-0.8	-5.2	-2.2

Fig. 2. NOAA-12 IR image from 1214 UTC, 26 September 1996 with letter-identified contrails (left) and contrails selected by automated algorithm (right, in green). Properties of identified contrails given in the table.

right with all of the contrails selected by the algorithm of Mannstein et al. (2000) shown in green. The optical properties and radiative forcings for each of the are summarized in the table below the images. In this scene, the optical depths and particle sizes vary by a factor of 3, while CRF_{LW} and the SW radiative forcing CRF_{SW} vary by factors of 5 and 10, respectively, depending on the optical properties and adjacent background. Thirteen different images were analyzed to obtain a variety of contrail types and backgrounds for a total of 55 different contrails. The results, summarized in Fig. 3, reveal that almost half of the contrails had $\tau < 0.25$ and $D_e < 30$ μm. However, several contrail optical depths exceeded 1.0 resulting in a mean of 0.46, which is 50% greater than the value usually assumed to represent linear contrails. A few contrails were composed of large ice crystals, but most were smaller than 50 μm. The mean of 35 μm is a bit more than half of the global average cirrus cloud effective particle size of ~60 μm (e.g., Minnis et al. 1997). Although 55% of the contrails had $IWP < 3$ gm^{-2}, the mean value is 7.9 gm^{-2}.

Spreading Contrails

The estimates of contrail coverage over the USA still remain somewhat uncertain because of the overestimate incurred from the NOAA-12 analyses. Uncertainties in the automated detection scheme vary with satellite, however. Application of the method to the NOAA-14 AVHRR misses about 65% of the contrails, but does not produce any false positives. It is clear that the method needs to be carefully tuned for each satellite imager. Despite the overestimates obtained with NOAA-12 data, the observed coverage is probably less than the true value because of spreading. From the eight cases of spreading contrails tracked by Minnis et al. (1998) and Duda et al. (2000), it was determined that the contrail cirrus area increased by 2 to 4 times from the time the contrail was easily identifiable as a linear feature in the satellite data to its peak value, which typically occurred 3 to 5 hours later. The mean areal coverage for all of those cirrus clouds over the course of their average 8+ hours of existence was twice that of the original linear contrails. Thus, if linear contrails form each hour producing X areal coverage over a given region, then the true contrail-generated cirrus coverage at a given time could be as great as X+16X because the contrail cirrus in the region of interest would accumulate in the absence of advective processes. Such a scenario would be rare, however, because

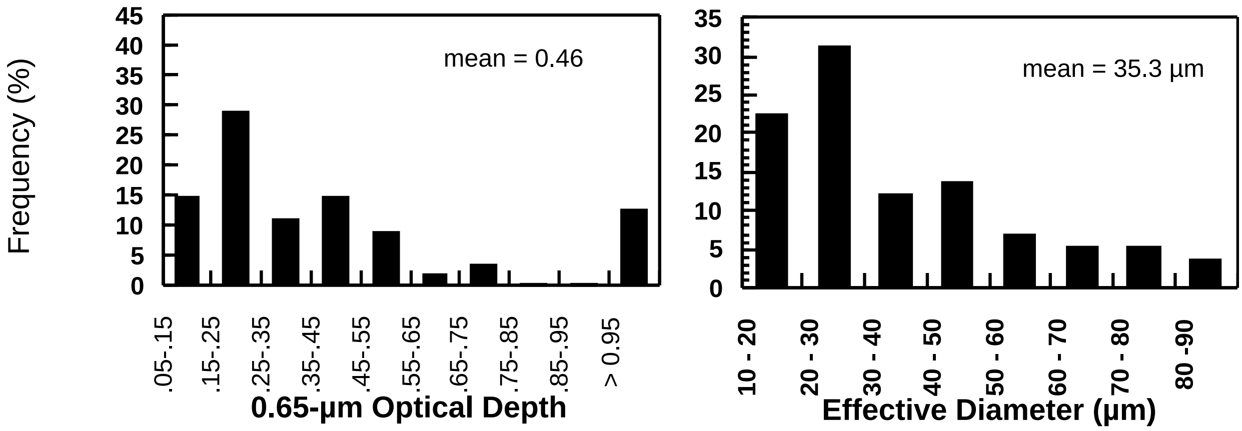


Fig. 3. Histograms of contrail optical depths and effective particle sizes derived from 13 NOAA-12 AVHRR images over the eastern USA.

most spreading contrail systems move swiftly and the old contrail cirrus would overlap the new linear contrails to some degree. Eight cases are not sufficient to produce a reliable spreading factor, however. More random samples including many different scenes are need to obtain an accurate value for the true change in cirrus cloud cover due to contrails.

The spreading contrails also show an increase in particle size with time with D_e reaching 60 µm or greater. The mean optical depth for the eight cases is 0.55. This larger value may be due to the moister conditions in which such contrails develop. Nevertheless, the differences in optical properties between the spreading and linear contrails will probably produce different radiative effects.

Future Research

Additional research is underway to match linear contrails with coincident air traffic, couple meteorological state variables with the contrail observations from satellite, and to compare infrared-only techniques with the visible-infrared methods for computing contrail optical depths.

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References

Duda, D. P., P. Minnis, and L. Nguyen, Estimates of cloud radiative forcing in contrail clusters using GOES imagery, *J. Geophys. Res.*, in press, 2000.

Gierens, K., R. Sausen, and U. Schumann, A diagnostic study of the global distribution of contrails, Part II: Future air traffic scenarios, *Theor. Appl. Climatol.*, **63**, 1-9, 1999.

Minnis, P., U. Schumann, D. R. Doelling, K. M. Gierens, and D. W. Fahey› Global distribution of contrail radiative forcing. *Geophys. Res. Ltrs.*, **26**, 1853-1856, 1999.

Minnis, P. and W. L. Smith, Jr., Cloud and radiative fields derived from GOES-8 during SUCCESS and the ARM-UAV Spring 1996 Flight Series. *Geophys. Res. Ltrs.*, **25**, 1113-1116, 1998.

Minnis, P., D. F. Young, B. A. Baum, P. W. Heck, and S. Mayor, A near-global analysis of cloud microphysical properties using multispectral AVHRR data. *Proc. AMS 9th Conf. Atmos. Radiation*, Long Beach, CA, Feb. 2-7, 443-446, 1997.

Minnis, P., D. F. Young, L. Nguyen, D. P. Garber, W. L. Smith, Jr., and R. Palikonda, Transformation of contrails into cirrus during SUCCESS. *Geophys. Res. Ltrs.*, **25**, 1157-1160, 1998.

Sausen, R., K. Gierens, M. Ponater, and U. Schumann, A diagnostic study of the global distribution of contrails, Part I: Present day climate, *Theor. Appl. Climatol.*, **61**, 127-141, 1998.